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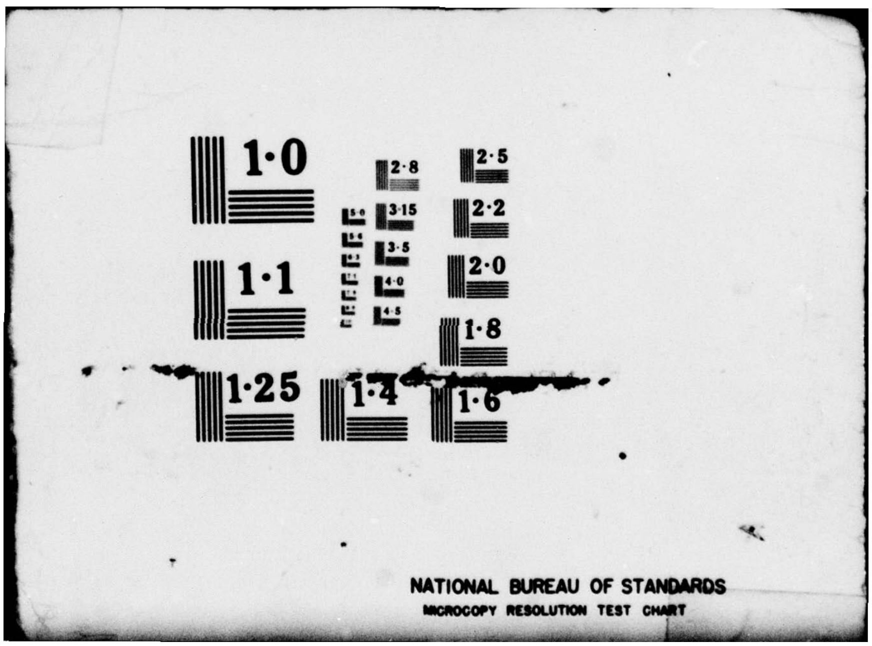
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by

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Preprint

M. L. Report No. 2205

August 1973

ML-2205

18 p.

Contract No. N00123-72-C-0866

Contract No. N00014-67-A-0112-0039

Contract DAHC 04-71-C-0005

Presented at:

Fifth International Symposium on
Acoustical Holography and Imaging
Palo Alto, California
July 18-20, 1973

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INTRODUCTION

We describe in this paper a new technique for processing acoustic information from a piezoelectric array. The device we shall describe is capable of presenting dynamic, nearly real time images of acoustic objects whether they be internal body organs in medical applications, wreakage in the sea, or flaws in non-destructive testing. The present device is capable of 1 mm resolution at distances of 20 cm and operates without the use of an external focusing element or an intermediary hologram. In the experimental results reported here two dimensional images are obtained using electronic scanning in one dimension and mechanical scanning in the other dimension. We will describe near the end of this paper how a fully electronic two dimensional scan may be implemented. The sensitivity of the imaging apparatus is expected to be sufficient to insure low sound power levels while still obtaining high quality images.

ELECTRONIC SCANNING AND FOCUSING OF ACOUSTIC BEAMS

In our system the acoustic image information is received by an array of piezoelectric detectors. The major difficulty in constructing such an acoustic imaging device is to scan this array in an efficient and economical manner. The technique we have chosen uses an acoustic surface signal wave traveling along an acoustic surface wave delay line as the basic scanning element. A schematic-pictorial diagram of the essential elements of the device is shown in Fig. 1. We will confine our attention for the moment to a one dimensional array and consider the two-dimensional problem later. A series of equally spaced taps is placed along the delay line, each tap corresponding to an individual transducer. The taps locally sample the acoustic surface wave amplitude and phase and these local signals are mixed by simple diodes with the signals from the corresponding detectors. The tapped surface wave line performs two functions: i) it converts a time varying signal to a spatially varying signal by its delay properties and ii) it samples this spatially varying signal at various points via the taps and applies these signals simultaneously to all of the diodes. This allows us to add the electrical signals from the individual elements while performing the necessary signal processing locally.

Also across each diode is connected one of the elements of the receiving transducer array. Hence two separate electrical signals are applied to each diode. The first, typically at about 4 MHz, arises from the acoustic object which we wish to image and the second, typically at 50 MHz, arises from the surface wave delay line which scans and processes the image information. The diodes serve as local mixers to generate sum and difference frequencies, typically 54 and 46 MHz. The electrical imaging output of the device is received at one of these two frequencies.

In order to understand the scanning operation of this device, we first consider the situation when a short acoustic pulse is sent along the delay line such that only one tap at a time is excited. In this case an output signal is obtained at the sum frequency only when the pulsed signal passes by a tap and there is a signal present on the corresponding detector.[1] As the pulse passes along the delay line, it scans each detector in turn so that the output may be used to intensity modulate a cathode ray tube, and hence display a visual image corresponding to one line of the acoustic image. The acoustic pulse thus acts like the scanning electron beam in a vidicon.

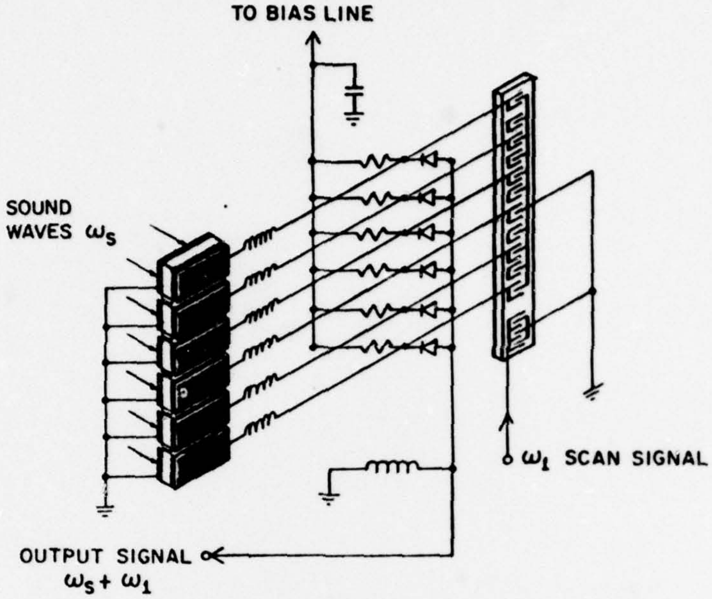


FIG. 1-- Schematic-pictorial diagram of acoustic imaging System

The arrays of acoustic detectors which are presently used to record an acoustic image serve much the same function as photographic film in recording an optical image.[2,3] The film merely records the light intensity which falls on a given element. An optical image of an object is formed by using the film in combination with an optical lens. This lens collects the optical energy falling on its entire surface and bends the ray paths originating from a source point in such a way that the energy is directed toward a given point on the photographic film. At the same time the lens alters the phase in such a way that all rays arrive at this point with equal phase - regardless of which point they pass through on the lens surface - and the signals add algebraically. The individual source points form corresponding points on the film, and the recorded image is a faithful reproduction of the object. In just the same way as in optics, an "acoustic lens" is required to form an image at the acoustic detector array. In conventional systems this is a plastic or liquid filled lens shaped similarly to an optical glass lens.

The action of an optical lens is usually explained by resorting to classical ray optics, and Snell's law, which itself is derived by determining the phase delay of a propagating wavefront.[4] Because the phase velocity of an optical wave is less in the lens material than in air, a ray incident on the lens suffers a phase delay proportional to the thickness of the lens at each point. Let us consider the two ray paths shown in Fig. 2: i) a ray passing through the axis of the lens, and ii) a ray passing through a point distance x from the lens axis. If the lens were not present, the phase delays for the two rays would be

$$\phi_1 = \frac{2\pi}{\lambda_0} [d_0 + d_i] \tag{1}$$

$$\phi_2 = \frac{2\pi}{\lambda_0} [(d_0^2 + x^2)^{\frac{1}{2}} + (d_i^2 + x^2)^{\frac{1}{2}}] \tag{2}$$

respectively. This latter expression can be simplified for values of x much smaller than d_0 and d_i (the so-called paraxial approximation) to:

$$\phi_2 = \frac{2\pi}{\lambda_0} \left[d_0 + d_i + \frac{x^2}{2} \left(\frac{1}{d_0} + \frac{1}{d_i}\right)\right] \tag{3}$$

It will be seen that ray (2) experiences an added amount of phase delay which is proportional to x^2 .

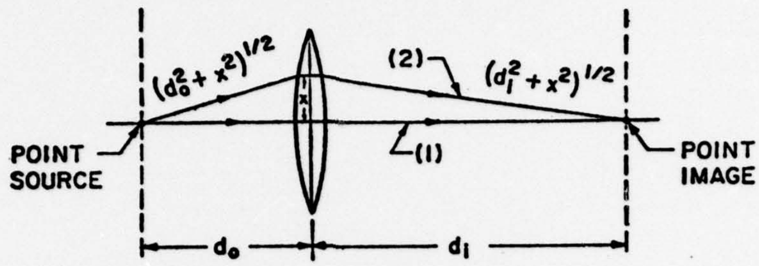


FIG. 2--Ray paths for an optical or acoustic lens

The phase delay through the lens compensates for this phase difference.[5] The thickness of a lens of the correct focal length is decreased as x increases in such a way that the phase shift, Φ_L, introduced by the lens has a value

$$\Phi_L = A - \frac{2\pi}{\lambda_0} \frac{x^2}{2} \left(\frac{1}{d_0} + \frac{1}{d_i} \right) = A - \frac{2\pi x^2}{2\lambda_0 f} \tag{4}$$

where f is the focal length of the lens and A is some constant. With this addition, the total phase shift from a point on the source to the corresponding image point is simply

$$\Phi \approx (2\pi/\lambda_0)\,(d_0 + d_i) + A \tag{5}$$

This phase shift is independent of the parameter of x, and all point on the lens surface produce rays which arrive in phase at the image point on the image plane of the film in a camera.

In the acoustic system we have learned how to compensate for the different phase delays in an analogous way. We consider again a point source of acoustic radiation and allow it to impinge on the array of piezoelectric detectors a distance d_0 from the source. If $x << d_0$, the phase at a point x on the detector as illustrated in Fig. 3, varies directly as

$$\phi_A = \omega_s t - (2\pi/\lambda_0)(d_0^2 + x^2)^{\frac{1}{2}} \approx \omega_s t - \frac{2\pi}{\lambda_0}\left(d_0 + \frac{x^2}{2d_0}\right) \tag{6}$$

where ω_s is the radian frequency of the acoustic wave.

As before we see that the phase is a quadratic function of the parameter x. It is this term that we must compensate in order that each element of the detector will contribute components which are "in phase" to the output signal. To accomplish this we convert the acoustic signal to an electrical signal at each piezoelectric element of the detector array. We then add an electrical phase shift to each element of an amount that compensates the $(2\pi/\lambda_0)\,(x^2/2d_0)$ term that arises from the different path lengths. In principle, this could be done with a computer after first converting to digital information. Our purpose here is to show that the acoustic surface wave delay line can be used to perform this function in a simple and direct manner.

When the piezoelectric array is illuminated by a point source, the amplitude of the imaging signals are almost constant from diode to diode, but the phase now corresponds to the sum of the phases ϕ_A of the incident wave and the ϕ_m of the surface wave signal. The aim is to adjust ϕ_m at each tap element so as to cancel the quadratic phase term $(2\pi/\lambda_0)\,(x^2/2d_0)$ in the incoming wave. We must therefore drive the mixing diodes with an electrical signal whose phase at any point is of the form: $\phi_m = A - (2\pi/\lambda_0)\,(x^2/2d_0)$. The phase of the mixing signal

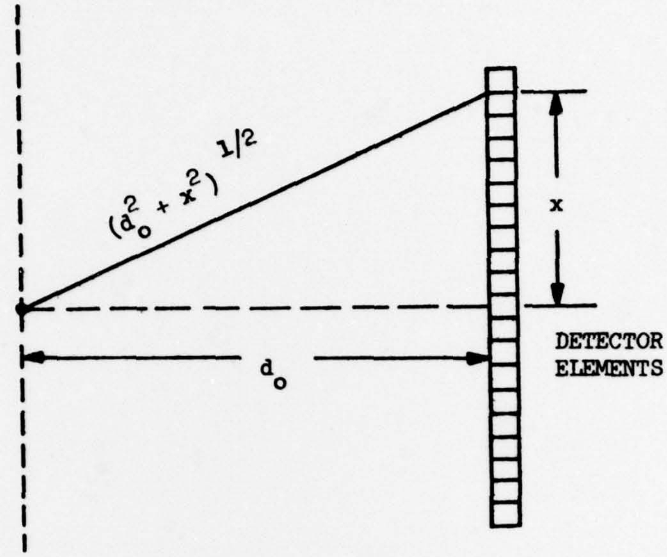


FIG. 3--Ray paths for a point source illuminating the acoustic imaging system.

is determined by the phase of the traveling wave sent along the delay line. As we have already seen, we need for lens action a quadratic variation of phase ϕ_m with x and, therefore, we must use a mixing signal which is modulated in a particular manner. If the surface wave frequency is constant the phase shift at each successive tap is a linear function of x. But if we inject a signal with a frequency which varies linearly with time, the so called "chirp" signal as $\omega = \omega_1 + \mu t$, the phase will vary quadratically with time. With this input the phase of the traveling wave becomes

$$\varphi_m = \left[\omega_1 + \frac{\mu}{2}\left(t - \frac{x}{v}\right)\right](t - x/v) \qquad (7)$$

or

$$\omega_m = \omega_1\left(t - \frac{x}{v}\right) + \frac{\mu}{2}\left(t^2 - \frac{2xt}{v} + \frac{x^2}{v^2}\right) \qquad (8)$$

The value of μ (the frequency sweep rate) is now adjusted so that the x^2 term in ω_m just cancels the x^2 term in ω_A. This is equivalent to adjusting the focal length of a lens. Rather than exciting one tap at a time as before, we use a long scan pulse, coded with the proper "chirp", so that all the taps are excited simultaneously. In this way we form the electronic equivalent of the optical lens and construct a system for summing in phase all the contributions from each array element.

An additional point to consider is that this quadratic phase signal is encoded onto a traveling surface wave. This means that the spatial position of the compensating waveform changes with time and in fact moves from one end of the array to the other at the velocity of the acoustic wave on the delay line. Hence the device interrogates a line located a distance d_0 from the array with d_0 determined by the frequency sweep rate and the lateral source position determined by the spatial position of the surface wave. The traveling surface wave acts like the scanning beam in a cathode ray tube.

A theoretical analysis of this imaging scheme has been carried out and we summarize below the technically important results. The resolution of the device is determined by the total aperture of the electronic lens, just as with any other type of lens.[6] The resolution is

$$\text{Resolution} = \frac{\lambda}{2 \sin(\theta/2)} \qquad (9)$$

or

$$\text{Resolution} \cong \frac{\lambda\, d_O}{D} \quad (\sin\theta/2 << 1 \text{ or } D << d_O) \tag{10}$$

where λ is the wavelength of the acoustic image signal, d_O the distance of the object from the array, and D the total aperture of the array. θ is the angular aperture of the lens, i.e. the angle subtended by the two extreme rays.

There is one significant difference however, between the optical analogy and the acoustic device. Due to the discrete nature of the receiving array, the number of resolvable spots is limited in the acoustic case to the number of elements in the receiving array. A typical case can be illustrated by a device operating at 4 MHz with an array 10 cm wide consisting of 100 elements. The device is capable of 1 mm resolution for objects 25 cm away. The unambiguous field of view is limited to 100 resolvable elements, or 10 cm. With the same array for an object distance of 15 cm , the device is capable of 0.6 mm resolution with an unambiguous field of view of 6 mm.

Much of the theoretical work can be summarized in contour plots. These curves are three dimensional in content with a vertical dimension proportional to output imaging power and two horizontal dimensions: lateral position along the array and range (or distance from the array). A typical example is shown in Fig. 4 with the calculations based on the experimental device described later. It consisted of a 30 element receiving array with center to center spacings of 2 mm . The array is assumed to be focussed on a point 25 cm away and the power output for an acoustic source exactly at this focal point is shaded for reference. Other sources at intervals of 2.5 cm on either side of this point contribute successively less to the image. This corresponds, of course, to out of focus, blurred images of these points. The width of the signal in the lateral dimension indicates the resolution (about 1 mm for the case illustrated). The depth of the field can

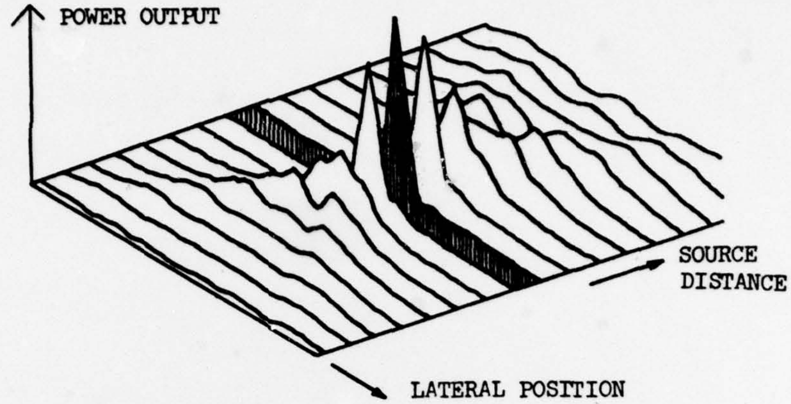


FIG. 4--Chirp rate set for 25 cm, (each line stepped by 1.25 cm).

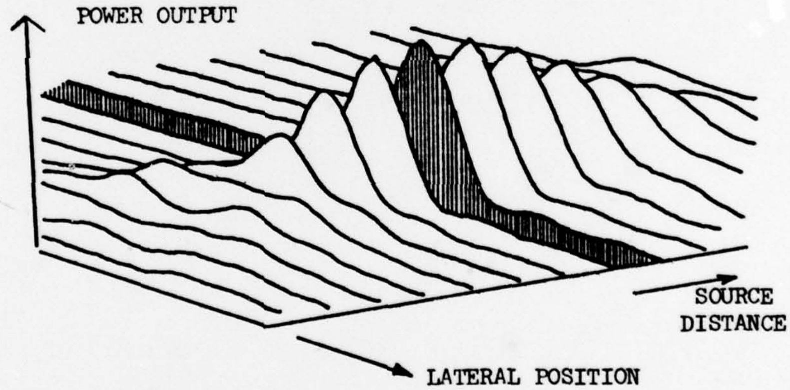


FIG. 5--Chirp rate set for 50 cm, (each line stepped by 2.5 cm).

easily be estimated as well as side-lobe structure. Another example of a contour plot is shown in Fig. 5 where the same array is assumed focussed at 50 cm. The resolution (pulse width) has worsened somewhat and the depth of field has increased as predicted above.

EXPERIMENTAL RESULTS

In order to test these ideas a thirty element linear array was constructed. It consisted of thirty 1.2 mm wide receiving transducers made from PZT-5, a line of parallel connected, forward biased 1N914 diodes, and thirty surface wave taps 3.2 mm apart on a bismuth germanium oxide substrate. The piezoelectric array was mounted onto a water tank and exposed to acoustic radiation from a 4 MHz source located in the water some distance in front of the receiving array. In the first experiments an acoustic point source was constructed by placing a diverging lens in front of a plane wave transducer. In Fig. 6 is shown the amplitude distribution of sound across the array. Each pulse corresponds to one of the array elements and as can be seen, approximately twenty of the thirty elements were illuminated covering a time interval of about 40 μsec. When a surface wave with the proper "chirp" signal was applied, the result of Fig. 7 was obtained. In this case the output at the difference frequency consisted of a single large pulse with a half-width of 2 μsec and a peak power level 25 dB above that obtained using the short scan pulse technique. This agrees well with the theoretical predictions. As the point source was translated parallel to the array, the image signal moved to an earlier and then a later time as required for scanning. Different "chirp" rates are required for different distances of the point source from the array. Shown in Fig. 8 is a plot of the chirp rate required for focussing versus source distance. The solid line represents the theoretical calculation and the brackets the measured values. Very close agreement is again obtained.

In order to demonstrate the potential of this device we have simulated a two dimensional imaging system in which one of the dimensions was scanned mechanically. Eventually, of course, both dimensions will be scanned electronically, but in order to demonstrate quickly the type of result possible, the mechanical scan was used.

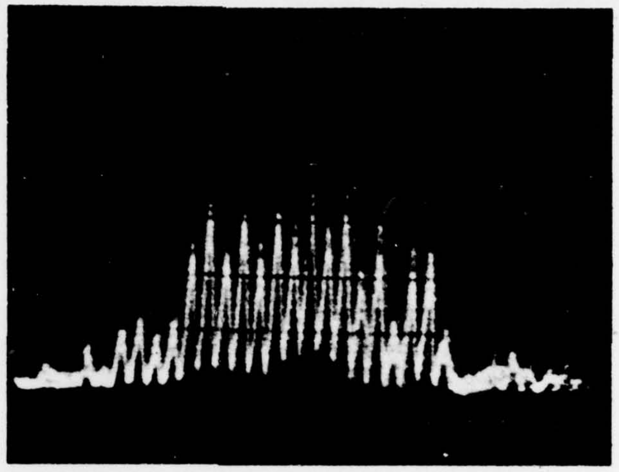


FIG. 6--Received signals from acoustic imaging device. Each pulse corresponds to one illuminated element in the array. Total time duration is 40 μsec.

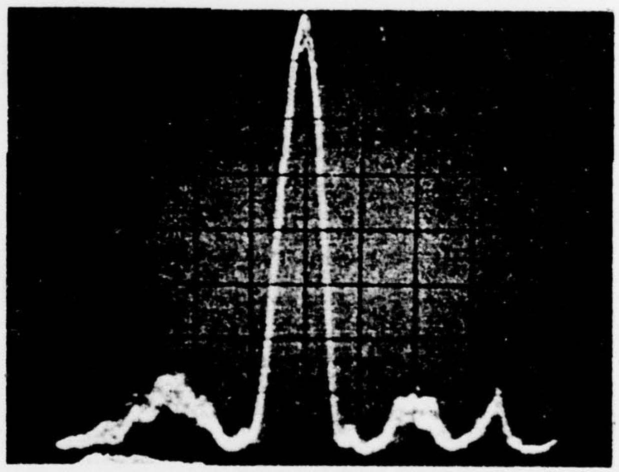


FIG. 7--Received pulse using chirp scan signal. Power output increased by 25 db and time duration of 4 μsec.

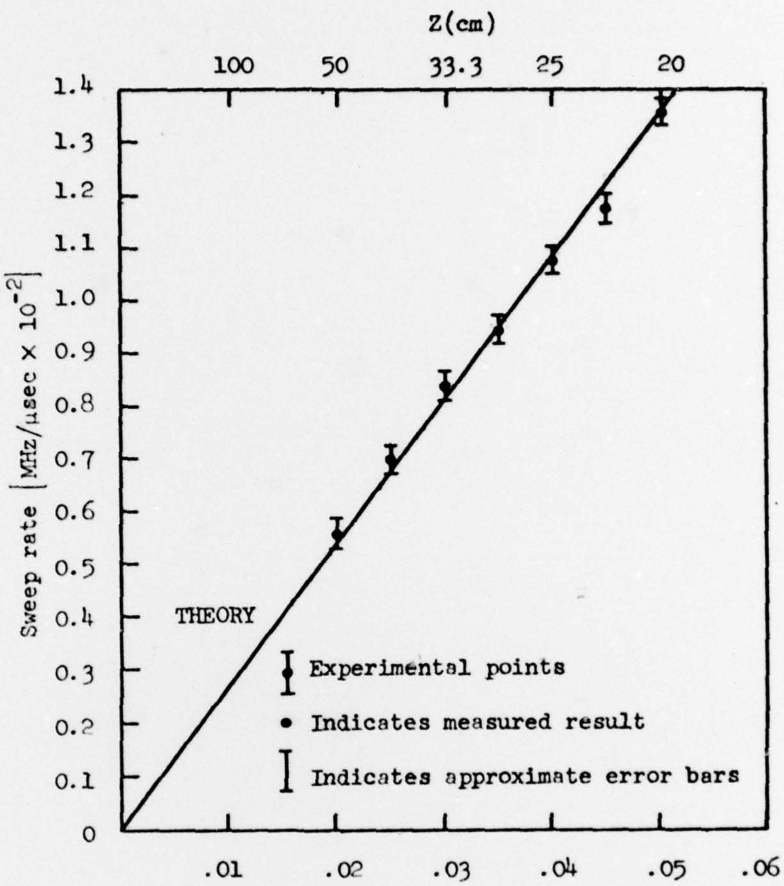


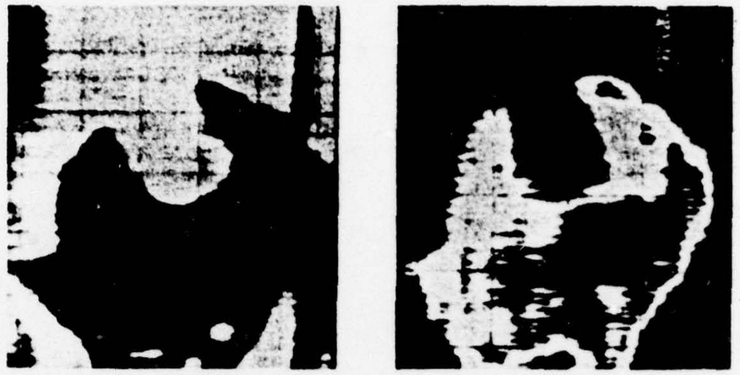
FIG. 8--Theoretical and experimental sweep rates for 4 MHz acoustic illumination.

The transducer array was illuminated by a plane wave transducer so that all the elements were exposed to sound. Twenty five (25) centimeters in front of the array between the transmitter and receiver, a small crescent wrench was immersed in the water and physically moved up and down. The vertical position controlled a battery potentiometer combination so that a dc voltage proportional to the vertical height of the object was obtained. The dc voltage controlled the vertical position of a cathode ray tube trace, thus providing a vertical scan. The horizontal scan was obtained electronically as before. The result is shown in Figs. 9a and 9b. The images are a reasonably good representation of the object. The handle of the wrench was approximately 9 mm wide and the open position at the top approximately 10.5 mm . The resolution of the system was measured to have been better than 1 mm as compared to a theoretical prediction of 0.75 mm.

In Fig. 9a the image signals were displayed directly by intensity modulating a cathode ray tube. The bright background corresponds to the plane wave illumination of the array and the dark region that portion of the plane wave obstructed by the wrench. In Fig. 9b the image signals were reversed in contrast electronically. Hence the background appears dark and the wrench bright. The dynamic range is greater in this latter image and internal structure to the wrench appears as a central dark region. This dark region corresponds to an opening in the wrench to provide motion for the carriage that opens and closes the open end.

TWO DIMENSIONAL ELECTRONIC SCANNING AND FOCUSING

A two dimensional device may be constructed by replacing the linear array with a square array as shown in Fig. 10. In the proposed scheme, on one side is deposited a series of parallel metallic strips and on the opposite side a two dimensional matrix of metallized regions. A separate diode is connected to each element of the matrix so that the appropriate signal processing can occur locally as before. One set of strips is connected to the taps on one of the surface wave delay lines. The focusing and scanning occurs in one dimension just as before except that many lines are processed simultaneously. The outputs are taken from a single line of the matrix to another



FIGS. 9a and 9b--Acoustic images of a small crescent wrench located 25 cm from the array. The photograph in Fig. 9b shows the internal structure of the wrench.

independent series of diodes and the taps of a second surface wave delay line. This second surface wave is also a "chirp" signal which scans and focuses the individual outputs from each line in the previously unfocussed dimension. If the acoustic image signal is at ω_s , the first surface wave at ω_1 , and the second at ω_2 , the output signal appears at $\omega_s + \omega_1 + \omega_2$. The output signal at a time t is generated from a point on the object with co-ordinate $x_o = v\,t$ and $y_o = v(t - \tau)$. Thus a line at 45^o to the x-axis is scanned. This line may be displaced by changing the delay time τ between the two surface wave signals and a complete raster is traced out.

CONCLUSIONS

A system has been described and demonstrated for linear electronic scanning and focusing of acoustic beams. Acoustic images of an object 25 cm in front of the array have been presented with a resolution of 1 mm . A two dimensional version has been described which will allow a fully electronic two dimensional system. It is expected that TV frame rates will be easily obtained in this system.

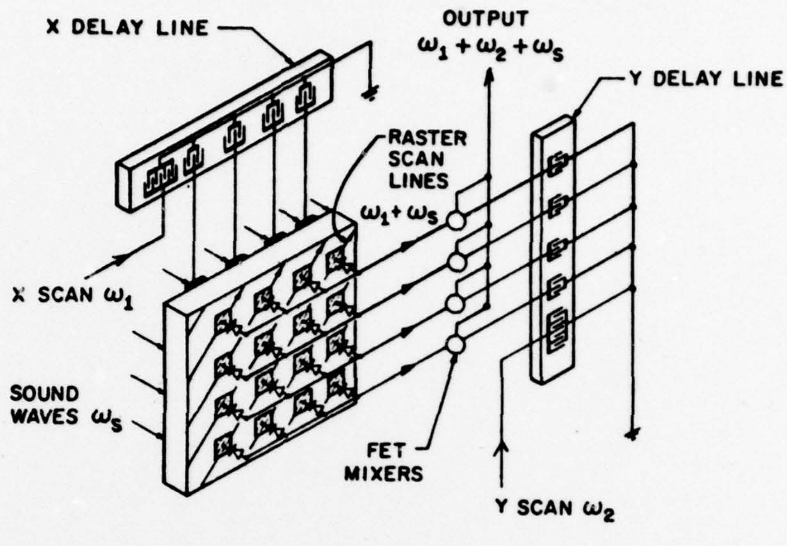


FIG. 10--Proposed two dimensional imaging scheme.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the fine technical assistance of D.J. Walsh and L.C. Goddard. We would also like to thank Harper Whitehouse of the Naval Undersea Laboratory for many stimulating conversations on the concepts in this paper.

This work was supported by the Naval Undersea Center, Contract N00123-72-C-0866 and the Office of Naval Research Contract N00014-67-A-0112-0039. We wish, also, to acknowledge the support of the U.S. Army Research Office, Durham, for support of the basic work on acoustic scanning that formed a foundation for this work.

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